contributions

The Traveling-Wave Linear Antenna*

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Summary—It is shown experimentally that an essentially traveling-wave distribution of current can be produced on a linear antenna by inserting a resistance of suitable magnitude one-quarter wavelength from the end of the antenna. A theory for the resistively-loaded dipole antenna is formulated on the basis that the inserted resistors (one in each arm) can be replaced by equivalent generators and that the resulting triply-driven antenna can be solved by the superposition of singly- and doubly-driven dipoles. Approximately 50 per cent of the power is dissipated in these resistors.

With a traveling-wave distribution of current on an antenna available, the properties of this antenna are then investigated and compared with those of the conventional linear antenna. It is found that the input impedance of the traveling-wave antenna remains essentially constant as a function of antenna length, whereas that of the conventional linear antenna varies considerably. It is also shown that the input impedance of the traveling-wave antenna varies only slightly over a 2 to 1 frequency band. The directional properties of the traveling-wave and conventional dipole are compared, and it is shown that a minor lobe does not appear in the radiation pattern of the traveling-wave dipole until it is much longer than the conventional dipole. Also, it is shown that where the directional properties of the conventional dipole are quite sensitive to a change in frequency, those of the traveling-wave dipole are not.

* Received by the PGAP, June 30, 1960; revised manuscripts received, October 3, 1960, and January 1, 1961. This research was made possible by support extended to Harvard Univ. by AFCRL under Contract No. AF19(604)4118.

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Introduction

THE properties of the linear antenna have been investigated in considerable detail by King.[1] It has been shown theoretically and verified experimentally that an essentially standing-wave distribution of current exists on short antennas of this type. This report deals with a linear antenna very much like the conventional one, except that it has been modified so that a traveling-wave distribution of current exists on all but its end quarter-wavelength, which has a standing-wave. The traveling wave is produced on the antenna very much as a traveling wave is produced on a transmission line. According to transmission-line theory, a pure traveling wave can be created by terminating the line in its characteristic impedance. If the line is assumed lossless, its characteristic impedance is a pure resistance. If the line were terminated in an open circuit, one could produce a traveling wave by placing a resistor equal to the characteristic resistance of the line in series with the line one-quarter wavelength from its end.

[1] R. W. P. King, "The Theory of Linear Antennas," Harvard University Press, Cambridge, Mass.; 1956.

A linear antenna is in two ways similar to an open-ended transmission line. First, it ends in an open circuit since the boundary conditions state that the axial current must go to zero at the end of the antenna. Secondly, a standing-wave distribution of current exists on the antenna. It seems reasonable that it may therefore be possible to create a traveling wave on a linear antenna by placing a resistor one-quarter wavelength from the end.

Unfortunately, the antenna does not have a characteristic resistance associated with it in the TEM sense of the transmission line. Therefore, the correct value of resistance is not immediately obvious. However, by considering simple antenna theory, it can be shown that a relation exists between the characteristic resistance R_c of a transmission line and the expansion parameter ψ of an antenna. The input impedance of an ideal, open-circuited transmission line is

$$Z_{\text{in}} = -jR_c \cot \beta_0 h,$$

where h is the length of the line and β_0 is the free space phase constant. The zeroth-order input impedance of a dipole is

$$Z_{\text{in}} = -j \frac{\zeta_0}{2\pi} \psi \cot \beta_0 h,$$

where h is the half-length of the dipole and ζ_0 is the free-space characteristic impedance. Therefore, R_c corresponds to $\zeta_0/2\pi\ \psi$.

The expansion parameter is a somewhat arbitrarily defined quantity which is related to the ratio of the vector potential at any cross section on the outside surface of the antenna to the total axial current in the conductor at that cross section. It can be shown that this ratio is reasonably constant over all parts of the antenna, except where the current is very small or zero. It can be shown further that $\psi \doteq \Omega - 2$, where $\Omega \doteq 2 \ln 2h/a$, where h is the half-length of a dipole, and a is its radius.[2] Since the expansion parameter is a function of the length of the antenna, while the characteristic resistance is independent of the length of the transmission line, it is obvious that this correspondence is not precise. It does suggest, however, an order of magnitude of the resistance required to approximate a traveling-wave distribution on the antenna, namely 60 ψ ohms. Since the quantity $\Omega - 2$ has a value in the range of 9 to 15 for reasonably thin dipoles, a resistance of the order of magnitude 6×10^2 ohms might be expected, for example, when $\Omega = 12$.

The theoretical distribution of current on the resistive-loaded antenna is calculated as follows. The resistor is first replaced by a constant-voltage generator. This is made possible by applying the compensation theorem of network theory, which states that an impedance in which a current I is flowing can be replaced by a potential difference equal to $-IZ$, without changing the electrical behavior of the network. In replacing each resistor by a constant-voltage generator, one obtains a dipole driven by three separate generators. Due to the linearity of Maxwell's equations, one can simplify the problem still further by applying the superposition theorem, which states that if several sources are present in a linear electrical network, the network may be solved by finding the currents or voltages in the network resulting from the presence of one source at a time, and then superimposing the results. The voltage generators omitted are replaced by connections of zero resistance. This enables one to treat the three-generator antenna as the superposition of two symmetrically-driven antennas; one driven by a single generator at the center, the other driven by two generators, each located one-quarter wavelength from the end. In order to analyze the doubly-driven dipole, superposition may be applied again. This time it is the superposition of two asymmetric dipoles. The asymmetric dipole can be solved approximately by treating its top and bottom parts separately, as if each were a base-driven antenna over an infinite, perfectly conducting plane. The current distribution has been calculated for a loaded antenna of half-length $h = 3\ \lambda/4$.[3]

Once a sound experimental setup is available, it is possible to produce a traveling-wave distribution of current on a linear antenna by inserting a series resistance one-quarter wavelength from the end of the antenna. The input impedance, current distribution and radiation field of this antenna then can be measured. From these data, the behavior of the traveling-wave linear antenna can be completely described. It is found that it differs significantly from the corresponding standing-wave antenna. In order to show these differences, numerous comparisons are made between the results obtained from the two antennas.

Experimental Results

Impedance and Admittance

The first experimental task was to determine which value of resistance, when placed one-quarter wavelength from the end of the antenna, produced a distribution of current which most closely resembled a traveling wave. Carbofilm resistors having dc values ranging from 3 ohms to 1 megohm were selected. The impedances of these resistors were measured at 600 Mc, and it was found that as the value of resistance increased, the dc and RF values began to differ. For resistances greater than 500 ohms, the correlation was very poor. The microwave impedance of the resistor was measured

[2] *Ibid.*, p. 77.

[3] E. E. Altshuler, "The Traveling Wave Linear Antenna," Cruft Lab., Harvard University, Cambridge, Mass. Sci. Rept. No. 7; 1960.

by locating the resistor at the end of the center conductor of a coaxial line in series with a short circuit, and then measuring the input impedance.

As has been previously mentioned, the input impedance of a traveling-wave transmission line is independent of the line length. It therefore seems reasonable to assume that the input impedance of a traveling-wave antenna is also essentially independent of its length. Therefore, by measuring the input impedance of a traveling-wave antenna as a function of its length, it is possible to determine which value of resistance, when placed one-quarter wavelength from the end of the antenna, changes the distribution of current so that it most closely resembles a traveling wave, without having to actually measure the distribution of current that exists for each resistor. After extensive measurements which involved the use of numerous resistors, it was found that the insertion of a resistor having a dc resistance of 240 ohms produced an antenna that had an input impedance which was almost independent of length. The RF value of the resistance differed by less than a few per cent from the dc value. It was also discovered that the impedance characteristics of this antenna were not sensitive to a small change from the optimum resistance.

With a 240-ohm resistor fixed at a distance of one-quarter wavelength from the end of the antenna, the input impedance of the antenna was measured at 600 Mc as the half-length h was changed from 0.5 λ to 1.5 λ in 0.05 λ increments. The normalized input impedance of the monopole above an image screen is plotted in Fig. 1. For the purpose of comparison, the measured impedance of the corresponding standing-wave antenna is also plotted on the same graph. The actual measured impedance of the monopole can be obtained by multiplying the normalized value by 123.6 ohms. The impedance of the corresponding dipole is simply twice that of the monopole. It is interesting to note that the impedance of the traveling-wave dipole has a value of approximately $(320+j110)$ ohms. Therefore, it seems reasonable to assume that the input impedance of the unloaded dipole should approach this value as the dipole length approaches infinity.

In order to investigate the broad-band properties of the traveling-wave antenna, the input impedance of an antenna of half-length, $h=31.25$ cm, was measured over a frequency range from 300 Mc to 900 Mc in 100 Mc increments. The result is shown in Fig. 2. The 240-ohm resistor was located 12.50 cm from the end of the antenna which corresponded to one-quarter λ at 600 Mc. Once again, the impedance of the corresponding standing-wave antenna is plotted on the same graph.

Distribution of Current

The distribution of current on the 240-ohm loaded antenna was measured for half-lengths ranging from $h=\lambda/2$ to $h=11\ \lambda/4$.[3] The relative amplitude $|I|/V_C^e$,

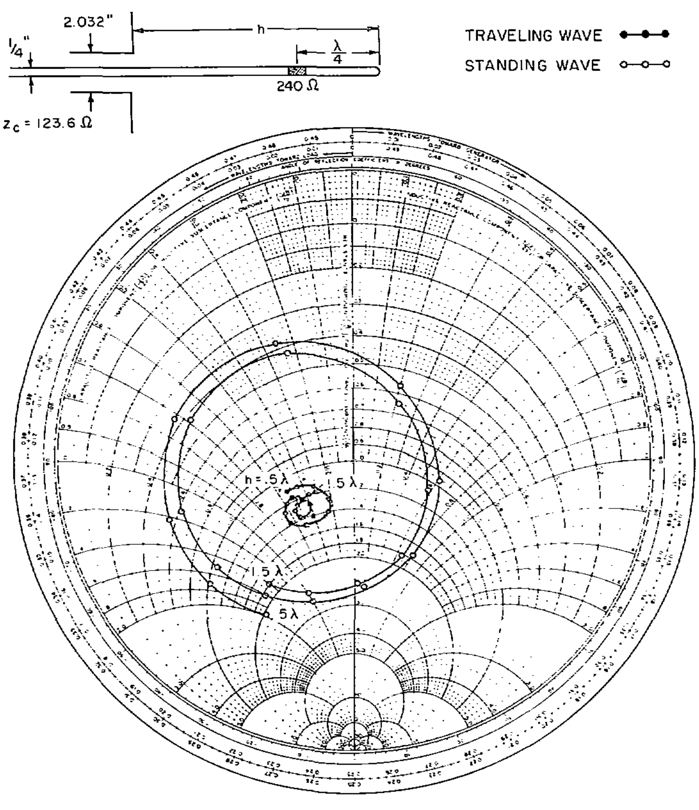

Fig. 1—Measured normalized impedances of traveling- and standing-wave linear antennas at 600 Mc.

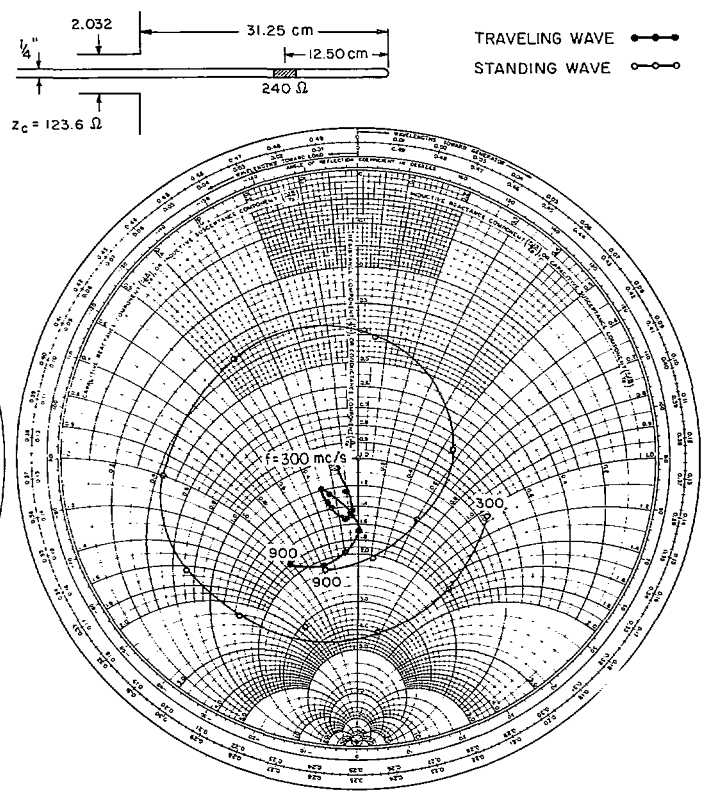

Fig. 2—Measured normalized impedances of traveling- and standing-wave linear antennas ($h=31.25$ cm).

phase $\theta = \tan^{-1} I'/I''$, and real and imaginary components I''/V_0^e and I'/V_0^e are plotted for antennas of half-length $h = 5\,\lambda/8$ and $11\,\lambda/4$ in Figs. 3 and 4 along with θ_T, which is a reference phase that varies linearly with distance along the antenna and thereby corresponds to the phase of a pure traveling wave.

Since the relative amplitude decreases almost exponentially with distance, and since the phase varies almost linearly with distance, the resultant distribution of current up to the resistor can be approximated by an exponentially attenuated traveling wave. At the resistor, the current amplitude remains continuous and then decreases nearly cosinusoidally to zero at the end of the antenna. The phase undergoes a change in slope at the resistor, since it changes from a linear variation with distance along the antenna to an almost constant value which is independent of distance. Therefore, the distribution of current on the end quarter-wavelength of the loaded antenna behaves very much like that on the unloaded antenna.

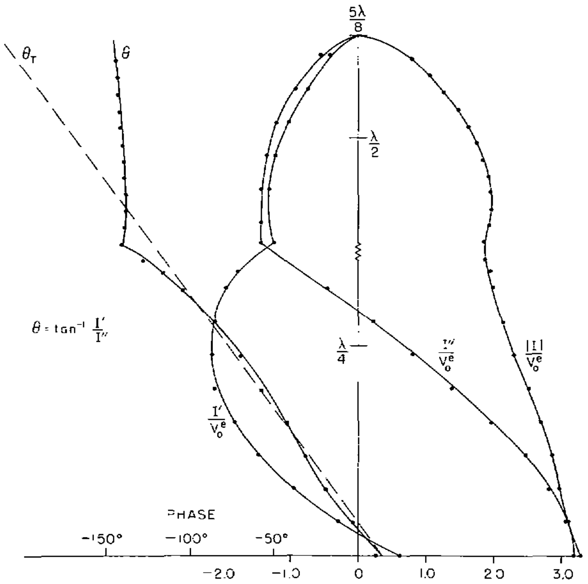

Fig. 3—Distribution of current for $h = 5\,\lambda/8$.

It is interesting to observe the behavior of the current in its transition from a standing wave to a traveling wave. This is illustrated in Fig. 5 for $h = 7\,\lambda/4$. As the inserted resistance is increased from zero ohms to 240 ohms, the standing-wave pattern of the relative current amplitude tends toward a standing-wave ratio of unity. As the resistance is increased above 240 ohms, the standing-wave ratio begins to increase. For the limiting case of $R = \infty$, one would expect the current distribution to resemble that of an antenna of half-length $h = 3\,\lambda/2$. It is for this reason that the standing-wave pattern shifts by 90° as the resistance is increased from below 240 ohms to above 240 ohms. The phase of the unloaded antenna oscillates somewhat sinusoidally about the linear traveling-wave phase. As the resistance is increased, the amplitude of the sinusoidal oscillation decreases until at 240 ohms it is essentially zero. As the resistance is increased above 240 ohms, the amplitude begins to increase. The shift that the sinusoidal-phase pattern undergoes when the resistance is increased from below 240 ohms to above 240 ohms is 180°. This corresponds to the shift that the phase pattern of an un-

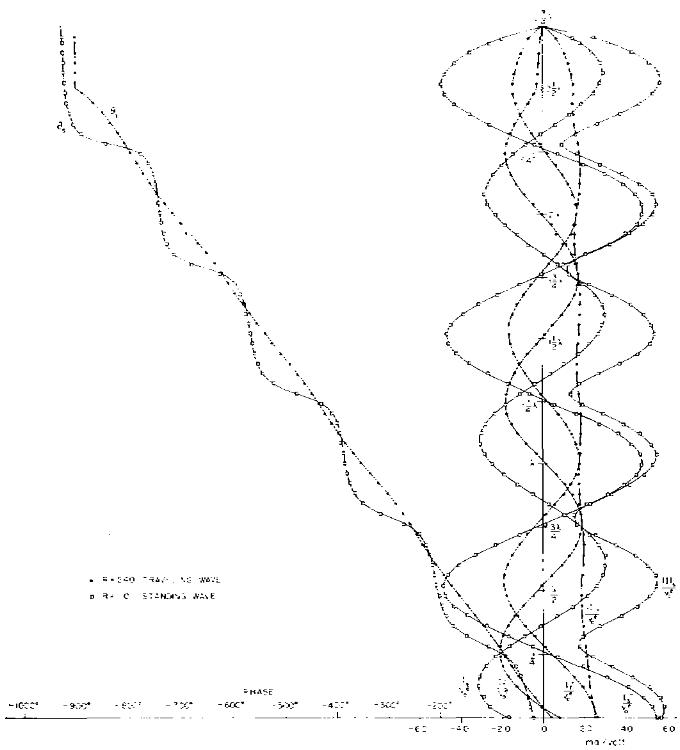

Fig. 4—Distribution of current for $h = 2\frac{3}{4}\,\lambda$.

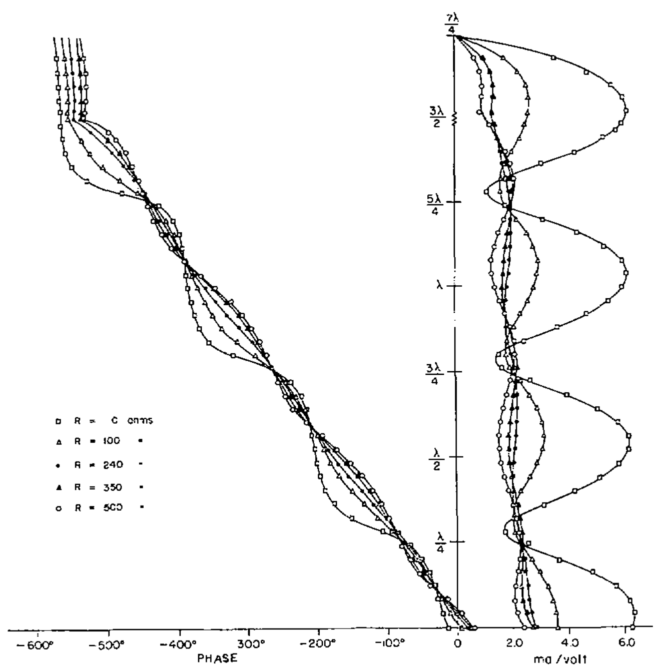

Fig. 5—Distribution of current for $h = 7\,\lambda/4$.

loaded antenna undergoes when it is reduced in length from $h=7\ \lambda/4$ to $h=3\ \lambda/2$.

It is expected that the standing-wave distribution of current on the unloaded antenna eventually approaches that of a traveling wave, as the antenna is made longer and longer. The current distributions of the unloaded and 240-ohm loaded antennas of half-length $h=11\ \lambda/4$ (the longest antenna that could be measured with the available equipment) are shown in Fig. 4. As can be seen, there is little indication that the unloaded antenna is beginning to approach a traveling-wave distribution. Therefore, it seems reasonable to assume that, as in the case of the open-circuited transmission line, the antenna must be extremely long before a traveling-wave distribution comparable to that obtained by the insertion of a 240-ohm resistor is produced.

Radiation Field

The relative power patterns of traveling- and standing-wave dipoles are shown in Figs. 6 and 7. As is expected, the directional properties do not differ very much for short dipoles, since the current distributions are somewhat alike. However, as the dipole becomes longer, a significant difference arises in the respective patterns. A minor lobe does not appear in the radiation pattern of the traveling-wave dipole until it is much longer than the corresponding standing-wave dipole. This behavior is in agreement with the power patterns which were calculated earlier.[8] It seems that the null, which ordinarily appears in the radiation pattern of the conventional dipole, is essentially filled in for the traveling-wave case. Therefore, the sidelobe in the conventional dipole pattern becomes part of the main lobe in the corresponding traveling-wave dipole pattern. It is interesting to note that some traveling-wave dipoles have half-power beamwidths of approximately 100°, which is considerably larger than the beamwidths that can be obtained with conventional dipoles.

The radiation patterns of traveling- and standing-wave dipoles were also measured as a function of frequency for dipoles of half-length $h=32.6$ cm. The power patterns of these dipoles are shown in Figs. 8 and 9. It can be seen that where the directional properties of the standing-wave dipole are quite sensitive to a change in frequency, those of the traveling-wave dipole are relatively insensitive. Therefore, the traveling-wave dipole, in addition to having a broad-band impedance, also has a broad-band radiation pattern. Naturally, as the frequency is changed from 600 Mc, the frequency at which the resistor is at an optimum distance of one-quarter λ from the end of the antenna, the traveling-wave distribution of current up to the resistor tends toward a standing-wave distribution. Therefore, one would expect the directional properties of both loaded and unloaded dipoles to be very similar at 1200 Mc, the frequency at which the resistor is $\frac{1}{2}\ \lambda$ from the end of the antenna.

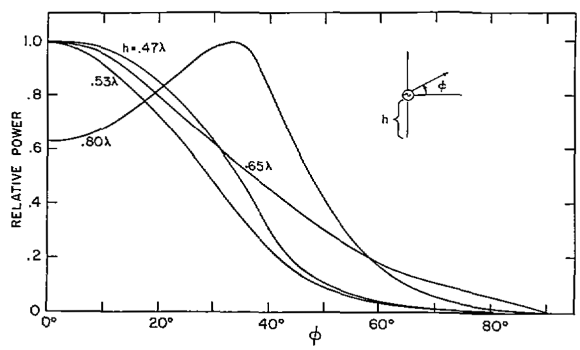

Fig. 6—Measured power pattern of traveling-wave dipole at 600 Mc.

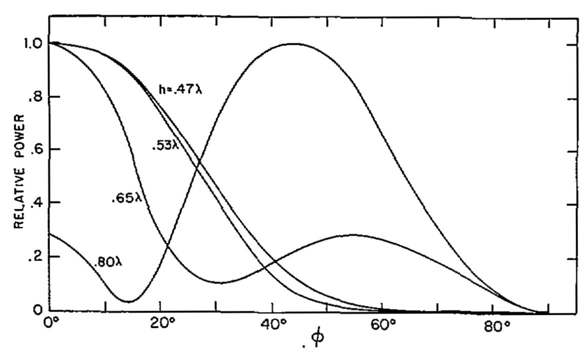

Fig. 7—Measured power pattern of standing-wave dipole at 600 Mc.

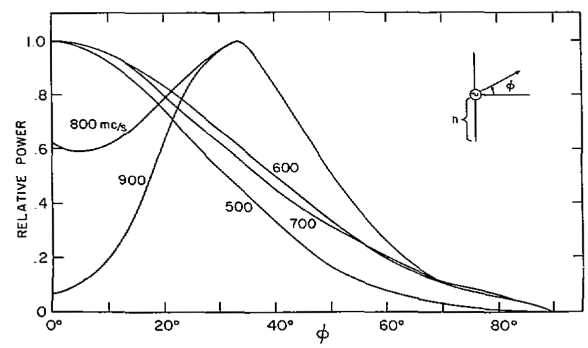

Fig. 8—Measured power pattern of traveling-wave dipole ($h=32.6$ cm).

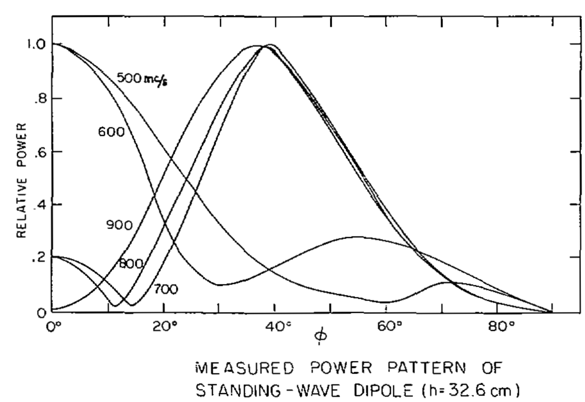

Fig. 9—Measured power pattern of standing-wave dipole ($h=32.6$ cm).

Efficiency

Let the efficiency of an antenna be defined as the ratio of the power radiated by the antenna to the power supplied to the antenna. The real power that is delivered to the antenna and is not radiated is usually dissipated in the form of heat. In general, the conventional linear antenna has a radiating efficiency of close to 100 per cent. The only losses which are present are those due to the finite conductivity of the antenna and the insulators which may be used to support it. The 240-ohm loaded antenna is approximately 50 per cent efficient.[3]

Conclusions

The results which have been reported here represent an extensive investigation of the traveling-wave linear antenna and its comparison with the conventional linear antenna. It has been shown experimentally that an essentially traveling-wave distribution of current can be produced on a linear antenna of $\Omega \doteq 10$, by inserting a resistance of approximately 240 ohms one-quarter wavelength from the end of the antenna. The radiation resistance of the traveling-wave monopole above an image plane is approximately 160 ohms. Therefore, the amplitude of the current at the resistor must always be less than the amplitude at the input of the antenna, since more power must be delivered to the antenna than can be dissipated in the resistor. For this reason, the current amplitude on the traveling-wave antenna is always attenuated. As the resistance is increased from its optimum value of 240 ohms toward infinity or decreased toward zero, the current distribution changes from an attenuated traveling wave to a standing wave. This transition is quite gradual. It is expected that the current distribution would undergo a similar transition when the resistor is moved, for example, from its optimum position of one-quarter wavelength from the end of the antenna to $\frac{1}{2}$ wavelength from the end.

The input impedance of the traveling-wave antenna has been shown to remain essentially constant as a function of antenna length. It is for this reason that this antenna is very broad-band compared to the conventional linear antenna. A broad-band antenna is in practice very desirable since it allows a good impedance match to be obtained over a wide band of frequencies. As has been pointed out earlier, the bandwidth limitation results from the fact that upon changing frequency, the electrical distance of the resistor from the end of the antenna is changed from its optimum length. Therefore, the essentially constant input impedance of the traveling-wave antenna as a function of length tends to the variable input impedance of the standing-wave antenna.

The directional properties of the traveling-wave dipole have been shown to be quite different from those of the corresponding standing-wave dipole. Whether they are more useful depends on the particular application for the antenna. The radiation properties of the traveling-wave dipoles are superior to those of the conventional dipole in two respects. First, the traveling-wave dipole can be operated over a relatively wide frequency range with only a small variation in its directional properties. Secondly, it can be designed to have a half-power beamwidth which is over 20° larger than that which can be obtained with a conventional dipole.

An investigation directed toward improving the efficiency of this antenna is presently being conducted. It may be possible to replace the carbon resistor by a more useful resistive element, for example, a resonant antenna with the appropriate radiation resistance. Therefore, energy ordinarily dissipated in ohmic losses will instead be radiated by the second antenna.

Acknowledgment

The author is indebted to Professor R. W. P. King for his very helpful guidance and encouragement during the course of this research.